INHIBITORY PROCESSES IN TASK SWITCHING

by

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STATEMENT OF DISSERTATION APPROVAL

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ABSTRACT

Do we selectively attend to the task we are currently performing only through the facilitation of goal relevant information or do we also actively inhibit irrelevant and potentially distracting information? The three experiments reported here addressed the role of inhibition in the task selection process, specifically in situations that involve task switching. The first two experiments used experimental designs that allowed us to investigate the role of backward inhibition in task switching in novel ways, finding that backward inhibition is associated with bivalent (Experiment 1A) and univalent (Experiment 1B) target stimuli. The use of bivalent stimuli in Experiment 1A also allowed for the evaluation of whether the recently abandoned task set was actively inhibited or whether it showed residual activation and resulted in proactive interference. Experiment 2 used explicit as well as transition cues ("repeat" or "switch") with three tasks in order to separate the processes of activating a specific new task from disengaging the previous task. This design also allowed us to measure inhibition during the trial on which it occurred as opposed to previous work on the inhibition of task sets which could only measure the cost of overcoming inhibition applied on previous trials. Results from all three experiments suggest that inhibitory processes associated with disengagement from old task sets play a significant role in the task switching process and, more generally, in cognitive control.

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INTRODUCTION

The human cognitive system is endowed with a limited capacity of information processing resources (i.e., Kahneman 1973), yet there are nearly infinite possible thoughts or objects in the environment that could be attended to. A prominent issue in of the study of attention has been how information relevant to one's current goals is let into the system for further processing while irrelevant information is "filtered" out (e.g., Broadbent, 1958; Treisman, 1960). Such a process of selective attention is necessary for coherent, efficient, and organized thought and behavior to occur. Selective attention, then, is a critical mechanism of cognitive control, operating by selecting goal relevant representations for processing while filtering out irrelevant information that may divert limited processing resources.

This problem of selective attention was highlighted in some of the earliest work in modern psychology. William James's (1890) often quoted definition describes attention as being "the taking possession by the mind in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought… [attention] implies withdrawal from some things in order to deal effectively with others." Attention then for James was not only a process of enhancing, facilitating, or activating relevant objects or thoughts, it was also a process of withdrawing from, or inhibiting, irrelevant ones. Inhibition played a central role in early psychological accounts; not only for James, but also for Wundt (1902) and others (see Smith 1992 for a historical review). Even in the

early days of modern psychology, however, theorists noted that definitive empirical evidence distinguishing facilitatory and inhibitory accounts of attention was lacking (Pillsbury, 1908). More recent work in selective attention focused on *where* in processing stream selective attention operates (e.g., Deutsch & Deutsch, 1963; Treisman, 1964) and *whether* processing resources are allocated in the process of selection (e.g., Johnston & Heinz, 1978), but the question of *how* selection is achieved, specifically whether through the facilitation of relevant information, the inhibition of irrelevant information, or both, has remained largely open (see Dagenbach & Carr, 1994).

The experiments reported here addressed the question of inhibition in the domain of task selection and task switching. Specifically we asked whether tasks are made available for action only through activating the newly relevant information or whether processes that inhibit old, irrelevant information are also involved when switching between multiple tasks. After reviewing relevant work from the task switching paradigm, we turn to empirical support for cognitive inhibition and techniques for measuring inhibition. We then discuss relevant work on the potential role of inhibition of task sets and contrast "activation-only" models of task switching with models that include inhibition. Finally, we report a series of experiments that address if, and under what conditions, the inhibition of irrelevant task sets may occur and that also offer new ways in which inhibition can potentially be measured.

Task Schema Activation and Inhibition

Norman and Shallice (1980/1986) proposed that schemas, or programs of action and thought, exist in mutually exclusive competition for selection. Because processing resources are limited, only one or very few of many possible schemas can be active at

any one time. According to their influential model, the selection of schemas for action could be modulated by a control mechanism they termed the Supervisory Attentional System (SAS), which could influence selection through "the application of extra activation and inhibition to schemas." This control mechanism's output is attention, which serves to modulate the activation and inhibition values of task schemas through its application. In addition to activation of relevant schemas, Norman and Shallice posited inhibition as a critical process of the attentional control system, and they noted that the specific role that inhibition plays in selection is still an open question.

The theoretical SAS model has been applied to experimental paradigms that examine how participants switch attention between multiple tasks. For example, Rogers and Monsell (1995) showed that longer response times (RTs) on task switch trials than on task repeat trials, even when the task switch was predictable. However, this "switch cost" decreased as participants had more time to prepare for the new task. The same basic effect was replicated by Meiran (1996; 2000) using unpredictable task switches by varying the interval between an instructional cue that informed the participant which task to perform and the subsequent target stimulus. These authors concluded that this RT benefit for increased preparation time suggested an active, endogenous control mechanism such as the SAS is operating to bias, "reconfigure," or adopt the new task set (see also Rubinstein, Meyer, & Evans 2001). Increased preparation time is assumed to produce faster RTs because the new task set will be more activated at the onset time of the target stimulus as a result of allowing more time for an activation mechanism to operate (for example, see the shape task in Figure 1).

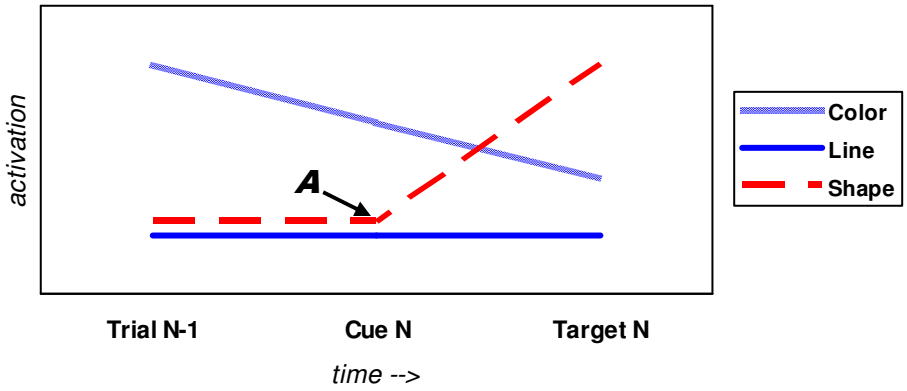


Figure 1. A model of an activation-only account of task switching among three (color, line, and shape) tasks. Attention (***A***) is only applied to activating the new (shape) task at the onset of the cue. Activation of the old task (color) passively decays but remains above baseline and above the activation level of the line orientation task at the onset of the new target.

A significant RT cost associated with switching tasks still is found even at the longest preparatory intervals (e.g., Meiran 1996; Rogers & Monsell 1995), however, which suggests that some part of the task set reconfiguration process cannot be prepared for in advance of the target stimulus. One explanation for these "residual" switch costs is that the activation of recently performed task sets persists through later trials, creating a form of proactive interference termed "task set inertia" (TSI) by Allport, Styles, and Hseih (1994; see also Allport & Wylie 1999). Although TSI is assumed to persist over multiple trials and long delays, it is also assumed to passively decay with time (for example, see the color task in Figure 1). From this view, increasing the amount of time between trials allows for further decay of recently performed but abandoned tasks and results in decreased costs in switching to a new task, presumably due to decreased interference caused by old task sets. It should be noted, however, that the TSI explanation is not mutually exclusive from accounts that assume conscious and goal-driven, or endogenous, activation. The two explanations may highlight dissociable components of

the switch cost, as some of the switch cost can be reduced by simply waiting for the passive decay of the old task set, while another component of the cost can be decreased by providing more preparation time for endogenous reconfiguration processes to operate (see Meiran 2000; Meiran, Chorev, & Sapir 2000).

Other researchers have suggested that there is no endogenous act of reconfiguring the new task during a switch, but rather that the benefits from cueing are the result of learned cue-encoding processes. Logan and Bundesen (2003) argued that task switch trials result in longer RTs than task repeat trials not because of a time and resource consuming endogenous process of activating the new task, but rather from a benefit of processing a repeated cue on sequential trials in task repeat conditions. By assigning multiple cues to each task, Logan and Bundesen found that switching the cue but repeating the task resulted in significant costs that in fact accounted for much of the switch cost. Their resulting model offers a simpler explanation of task switch costs that does not rely on any endogenous control processes. It should be noted, however, that even when such cue-switch costs are controlled for, significant task switch costs and associated reduction of such costs with increased preparatory intervals have still been obtained in certain experimental situations (Arrington, Logan, & Schneider, 2007; Mayr & Kliegl, 2003; Monsell & Mizon, 2006). Although cue switches may be associated with some performance cost, these results suggest a role for endogenous processes in task switching that cannot be accounted for solely by cue-encoding processes.

Cognitive Inhibition

If endogenous control processes are critical for activating new task sets, are other control processes responsible for inhibiting old task sets or schemas? Although there is

strong empirical evidence that inhibition does exist at the physiological and neural level, such that the activity of some neurons and circuits suppresses activity in other neurons, synapses, and circuits (for reviews see Cohen, 1993; Smith, 1992), the notion of cognitive inhibition has been more disputed. Given the compelling evidence for inhibition at the neural level, some researchers have posited that analogous inhibitory processes ought to occur at the cognitive level; that is, certain perceptions, actions, and thoughts could serve to suppress other perceptions, actions, and thoughts. Such extensions from the neural to cognitive level permeated not only the early work of James (1890) and others described above, but also much more recent influential accounts of inhibition (e.g., Anderson & Spellman, 1995; Dagenbach & Carr, 1994; Houghton & Tipper, 1994; Potts, St. John, & Kirson, 1989). However, many other authors have noted that the existence of neural inhibition alone is not sufficient evidence for the existence of cognitive inhibition (e.g., Breese, 1899; Diamond, Balvin, & Diamond, 1963; MacLeod et al., 2003).

The dispute concerning cognitive inhibition may stem from the ambiguous nature of the evidence in support of inhibition, primarily longer RTs associated with conditions in which inhibition is thought to occur. Critics of inhibitory models suggest that longer RTs reflect not a process of inhibiting of irrelevant information, but rather the need for additional facilitatory processing of relevant information in situations where the relevant and irrelevant representations are in conflict. If the criterion for the selection of one stimulus over another is a difference threshold between the activation level of the relevant and irrelevant stimuli, then the difference necessary for selection could be achieved either through increased activation of the relevant stimulus, through the

inhibition of the irrelevant, or through some combination of both processes. Proponents of activation-only accounts have tended to favor the parsimony of a single mechanism, while proponents of dual mechanism accounts (i.e., Houghton & Tipper, 1994) have cited the increased efficiency that having both facilitatory and inhibitory processes in the system would provide. Such conflicting accounts have emerged in several experimental paradigms, including the Stroop task, negative priming, and task switching.

Inhibition of Prepotent or Habitual Responses

In order to perform goal directed behaviors, individuals must be able to resist the strong habitual but currently inappropriate responses, whether these responses are caused by salient exogenous or environmental triggers or by overlearned, habitual associations. Although research has provided strong evidence for inhibition of prepotent responses at the neurophysiological level (e.g., Diamond, 1990; Diamond, Kirkham, & Amso, 2002), the strongest evidence for a comparable cognitive process may come from the Stroop paradigm (Stroop, 1935; see MacLeod, 1991 for review). In this paradigm participants are asked to respond to the ink or text color of an incongruent color word, (e.g., “RED” written in green ink), and robust RT and accuracy evidence suggests the habitual word reading process interferes with the less dominant ink color naming process. An inhibition account would assume that some attentional resources are devoted to inhibiting or suppressing the dominant word reading representation and response to allow for the less dominant response to ink color to be made. Some activation-only connectionist models of the Stroop task (i.e., Cohen, Dunbar, & McClelland, 1990), however, have accounted for performance with considerable accuracy without invoking inhibitory mechanisms. The Cohen et al. model suggests that interference in the Stroop task is resolved by allocating

attentional resources to the weaker, less habitual color naming task, thus providing enough activation that the participant can respond to the ink color instead of reading the color word. Because processing resources are assumed to be limited (i.e., Kahneman, 1973), allocating attention to the color naming task pathway is automatically and indirectly accompanied by decreased activation of other pathways (Braver et al., 2002; see also, Posner, 1978). This explanation, however, assumes that *all* other pathways would have decreased activation; no special inhibitory process is applied to decrease the activation of a particular pathway. If this explanation were to be generalized to task switching, where the strongest conflict is assumed to stem from the most recently performed task (i.e., Allport et al., 1994), it would suggest that inhibition is not applied to the switched-away-from task during switching, but rather that all other tasks result in decreased activation as a function of allocating processing resources to the goal relevant task. Although such activation-only models may be more parsimonious, they do not explicitly rule out the possibility that an inhibitory mechanism may also operate on the switched-away-from task. The amount of interference caused by differing potential sources of conflict, such as information from recently performed tasks versus information from tasks not performed as recently, have rarely been directly compared (see Mayr & Keele, 2000), so it is difficult to know whether all irrelevant information is equally deactivated or whether more recently performed tasks may receive increased inhibition.

Negative Priming

Negative priming, or the tendency for a slowed response to a stimulus (or stimulus aspect) that previously had been ignored (Neill, 1977; Tipper, 1985; see also Tipper 2001), has provided some of the most often cited evidence for inhibition.

Houghton and Tipper (1994), perhaps the strongest proponents of inhibition-based models of negative priming, argued that active inhibition is applied to the ignored stimulus or dimension, and that this inhibition persists into subsequent trials, thus slowing responses to previously ignored items. Although their model is less parsimonious than an activation-only (or in their terms, "amplification" only) accounts, they argue that a dual mechanism, involving both amplification and inhibition is more efficient in the sense that signal and noise can be separated more quickly, resulting in a faster time course for reaching a threshold for selection.

Leading alternative accounts of the negative priming phenomena, however, offer a non-inhibitory explanation based on episodic retrieval (e.g., Neill & Mathis, 1998; Neill & Valdes, 1992; Neill, Valdes, Terry, & Gorfein, 1992; see also, Logan, 1988, 1990, 2002). These accounts suggest that the ignored stimulus on trial N-1 is not inhibited, but rather that a trace of how a stimulus was processed in past instances is retrieved with the new presentation of that stimulus. For example, from this view, if the word "chair" was ignored on trial N-1, and then served as the response-relevant stimulus on trial N, "chair" would be retrieved with a "do not respond" goal or "tag" from the previous instance. This tag would have to be overcome before a response could be made. Thus, specific target words are associated with different goals: they must be ignored in some cases and responded to others. Such conflict requires additional time to resolve, resulting in the observed negative priming performance cost. In this view, as in non inhibitory accounts of Stroop, the cost stems from conflict resolution and not from the inhibition of irrelevant information, though these differing explanations of the observed RT cost are methodologically difficult to disentangle in traditional negative priming paradigms (see

Tipper, 2001).

Inhibition of Task Sets

Turning back to task switching, Mayr and Keele (2000) proposed that abandoned goals and task sets do not passively decay, but rather they are actively inhibited. They proposed an endogenous control process that inhibits previously active task sets, effectively deleting no longer relevant information from working memory (i.e., Hasher & Zacks 1988; Hasher, Zacks, & May 1999) such that interference from no longer relevant information is reduced, allowing for more efficient processing of information related to the new task. This model stands in contrast to the TSI account proposed by Allport et al. (1994), which suggests that old task sets passively decay. Because the design of Allport et al. employed only two tasks, they could not contrast interference stemming from a recently abandoned task set with interference from an old task set not as recently performed. Empirical support for Mayr and Keele's model comes from the backward inhibition (BI) effect that they observe across five experiments. In their experiments participants are required to alternate among three task sets (e.g., hypothetical tasks "A," "B," and "C"), thus allowing the researchers to compare switch costs associated with switching back to a recently disengaged from task (e.g., **A**-B-**A**) with costs associated with switching to a task that has not been recently disengaged from (e.g., C-B-**A**). Mayr and Keele demonstrated that the former condition is associated with significantly greater costs, and conclude that the additional cost was incurred because participants had to overcome the inhibition associated with a recently disengaged task (**A**) in order reactivate it.

Norman and Shallice (1980/1986) asserted that when one schema is selected for action, all other schemas are inhibited. Mayr and Keele's (2000) results suggested that while all other schemas may be inhibited to some degree, the task schema most recently performed is inhibited to an even greater extent, below the activation level of other tasks that have not recently been performed (see Figure 2). However, measuring this type of inhibition requires switching among at least three tasks. Overcoming this inhibition could constitute an important component of the switch cost (see also, Arbuthnott & Frank, 2000) that could not be controlled for in the more commonly used two-task experimental designs used to study task switching.

Mayr and Keele's (2000) evidence of backward inhibition may constitute nascent support of such inhibitory processing, but many unanswered questions regarding the nature of inhibition in the task switching process still remain. First, some experiments have identified boundary conditions where BI is absent, such as when a motor response to an activated task was not required in a no-go condition (Schuch & Koch, 2003), while others have suggested that task set inhibition is either weak or absent, is not adaptive, or can easily be overcome (Lien, Ruthruff, & Kuhns, 2006). It should be noted that Mayr and Keele's experiments utilized trivalent stimuli, or stimuli that contained aspects of all three tasks. While they were able to demonstrate the presence of inhibition through increased reactivation costs for previously active task sets, their design did not allow for the potential benefits of inhibition – that is, the reduction of interference stemming from previously performed tasks – to be measured because their target stimuli contained interfering information from *both* irrelevant tasks. The following experiments sought to

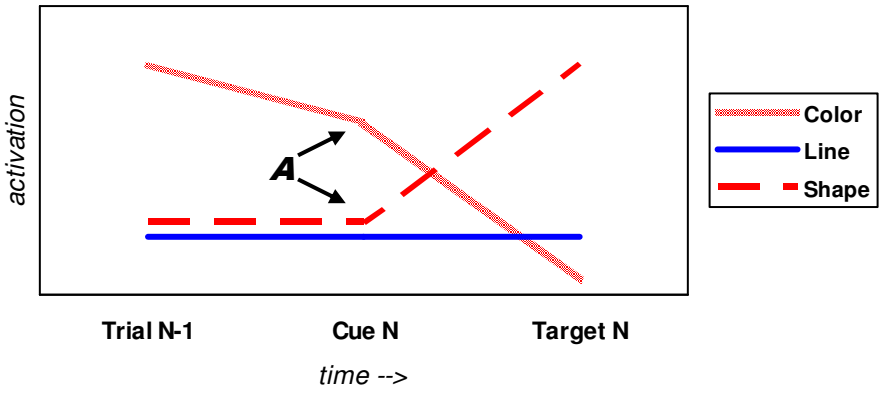


Figure 2. A model of task switching with activation plus inhibition of the disengaged task (color). Attention (***A***) is applied to activating the shape task *and* inhibiting the color task at the onset of the task cue. Note that the disengaged task (color) is inhibited below baseline (and below the activation level of the line orientation task) at the onset of the new target.

replicate the backward inhibition effect in novel situations and to examine the potential benefit of interference reduction created through the inhibition of old task sets.

Overview of Experiments

The first set of experiments (1A and 1B) served to replicate the BI effect and examine important boundary conditions relating to when endogenous inhibitory processes may occur in the task switching process. Experiment 1A also addressed whether inhibition served only to disengage from the previous task schema or whether it also resulted in decreased interference from recently abandoned tasks (i.e., decreased task set inertia). Through using bivalent, as opposed to trivalent stimuli with a three task design, we could control for whether the irrelevant information in the target stimulus was related to a previously abandoned (and presumably recently inhibited) task, or from a task that was not as recently abandoned. Thus we were able to measure whether or not inhibition of task sets was adaptive in controlling for interference of no longer relevant

information. Other authors (Lien, Ruthruff, & Kuhns, 2006) have posited that the incentive for inhibition should be stronger following bivalent trials because these trials contain information that needs to be ignored in order to make a response. However, because inhibition is assumed to occur at the abstract task set level (see Mayr, 2007; Mayr & Keele, 2000) it may occur regardless of whether the stimulus of a previous trial contained irrelevant task information or not. Experiment 1B explicitly examined the role of inhibition when responding to univalent stimuli.

Previous observations of BI (Arbuthnott & Frank, 2000; Mayr & Keele, 2000; Schuch & Koch, 2003) measured the effect indirectly by examining the time it takes to overcome inhibition on a previous trial. Moreover, inhibition has been shown to decay over the trial intervals typically used in task switching experiments (see Mayr & Keele, 2000, Experiment 1B), such that some of the inhibition applied in trial N-1 will have decayed by the time that overcoming this inhibition and reactivating the old task is measured on the current trial. Experiment 2 served to provide a more direct measure of inhibition, by measuring inhibition during the trial on which it occurred, as opposed to measuring the process of overcoming inhibition that occurred on previous trials. In addition, the cueing paradigm and design utilized in Experiment 2 allowed us to separate the often confounded processes of disengaging the previous task from the processes of reconfiguring the new task set.

EXPERIMENT 1A

Mayr and Keele (2000) suggested that backward inhibition is evidence for an endogenously controlled process of inhibiting the abandoned task set. In essence, they argued that in light of their results, task switching cannot be an "activation-only" process of set selection. However, task activation or reconfiguration (i.e., Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001) and task set inhibition may not be the only two processes responsible for the RT costs associated with task switching (see Meiran, 2000, for discussion). Task set inertia (TSI) of previously active tasks may result in proactive interference that must be resolved in responding to the new task (Allport, Styles, & Hseih 1994; Allport & Wylie, 1999). If a previous task set retains residual activation and occurs in the stimulus as an irrelevant dimension, then the values associated with it could create interference. For example, consider a trial in which the target consists of red vertical lines and the task is color discrimination. If the task on the previous trial (N-1) was line orientation, then the residual activation of the line orientation task may result in interference stemming from the vertical line "distractor" in the color task stimulus. In this example, a task set inertia explanation would predict more interference from a line orientation distractor than from a shape distractor because line orientation was the most recently performed task (i.e., trial N-1) and thus should have more residual activation or inertia. It is also important to note that TSI is assumed to passively decay over time.

Mayr and Keele (2000) argued that the use of inhibition precludes TSI effects: If the previous task set is actively inhibited, it cannot retain residual activation that interferes with the new task. The studies by Allport et al (1994), as well as most other task switching designs (e.g., Meiran, 1996, 2000; Rogers & Monsell, 1995) could not measure BI, as these experimental designs only employed two tasks. Thus, participants were, due to the experimental design, always switching back to the most the recently abandoned task set (see Mayr & Keele, 2000). In contrast, Mayr and Keele's experiments employed not only three tasks but also trivalent stimuli, with every stimulus containing values associated with all three tasks. Incorporating three tasks allowed Mayr and Keele to compare switching back to the most recently abandoned task (A-B-A) to conditions in which participants switched to the task not as recently abandoned (C-B-A). However, using trivalent stimuli had a drawback in that the degree of potential interference carried over from the previous trial could not be isolated because each stimulus has dimensions of both of the irrelevant tasks. In this experiment we used three tasks in order to potentially replicate the BI effect, but we did so using bivalent stimuli to allow us to measure interference from the previous trial as well as BI. This manipulation allowed us to examine whether interference in the form of TSI was actively controlled through inhibiting recently abandoned tasks, or whether such inertia interfered with subsequent trials. If the active inhibition model is correct, one would expect the values of the recently abandoned task to cause *less* interference when it is the irrelevant (distracting) dimension on the next trial, because the task and its values were recently inhibited (see Figure 2). However, if the passive decay model (Allport et al., 1994) is correct, one should expect values from the recently abandoned task to cause *more* interference, because it should

have the greatest inertia from being recently performed (see Figure 1). The design of this experiment thus allowed us to investigate the BI effect using bivalent as opposed to trivalent stimuli, and allowed us to separate active inhibition from passive decay or TSI models.

Method

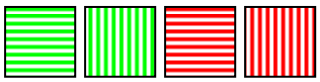
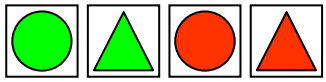
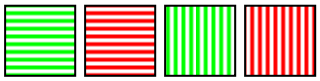
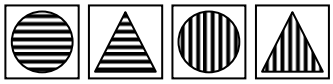
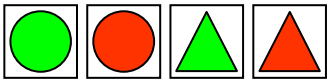
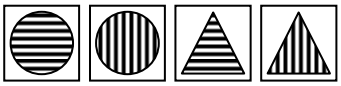
Apparatus and Participants

The experiment was run on E-Prime version 1.0 software and displayed on an 18" Gateway monitor. Responses were made on a custom built Psychological Software Tools serial response box expansion with six button switches. Participants sat a comfortable distance from the monitor and response box. Thirty-six volunteer participants, recruited from undergraduate psychology classes, participated and received one hour of extra course credit for their time.

Tasks and Stimuli

The experiment utilized three tasks, each with two associated values – red and green for the color task, horizontal and vertical for the line orientation task, and triangle and circle for the shape task. Each stimulus had one relevant dimension, which was cued in advance of the target, and one irrelevant dimension from one of the other two non-target tasks. For notation purposes, the letter designating the relevant task will be listed first, denoted with a capital letter, while the irrelevant dimension will be listed second in lower case. For example, a color task stimulus with a shape distractor would be denoted "Cs," while a line orientation task stimulus with a color distractor would be listed "Lc." Stimulus examples are listed in Table 1.

Table 1. Stimuli for Experiment 1A.

Stimulus	Task/Cue	Targets	Responses
Cl	COLOR		Green/Red
Cs	COLOR		Green/Red
Lc	LINE		Horizontal/Vertical
Ls	LINE		Horizontal/Vertical
Sc	SHAPE		Circle/Triangle
Sl	SHAPE		Circle/Triangle

Procedure and Design

After informed consent was obtained, the participants were given written instructions describing the tasks they were to perform. They completed one training block of 20 trials for each task with no task switches (i.e., 20 consecutive color trials, 20 consecutive line orientation trials, etc.), and a final training block of 40 trials that did contain task switch trials. These training blocks were excluded from the statistical

analyses. The order in which the participants saw the tasks in the no-switch blocks was counterbalanced across participants. These training blocks served to familiarize the participants with the trial procedure, the tasks, and the responses associated with each target type. Each target type (red, green, horizontal, vertical, circle, and triangle) was associated with a single button on the response box (i.e., univalent response mapping). A diagram of the response box is pictured in Figure 3. Each response key was located equidistant from a center finger rest pad, and the locations of the responses were rotated across participants to counterbalance the location of each task on the response box. Participants were instructed to respond using the index finger of their preferred hand to press the response keys.

After training was completed, participants then completed ten experimental blocks consisting of 50 trials each, for a total of 500 trials. They were given an opportunity to take a brief, self-timed break between each block, and cumulative RT and accuracy were reported to the participants after each block to motivate them to respond quickly and accurately and keep them focused on the experimental task. During the experimental blocks tasks were presented in a pseudo-random order and each of the 10 blocks contained a unique sequence of trials, such that neither the task, target stimulus, nor cue-target interval (CTI) of the upcoming trial could be predicted based on the previous trial or on previous blocks. These design measures were taken to avoid implicit or explicit sequence learning effects. The task cue for the upcoming trial was presented 500 ms after the response to the previous trial and appeared either 500 ms or 1000 ms before the onset of the target stimulus, creating two CTI (short and long) conditions.

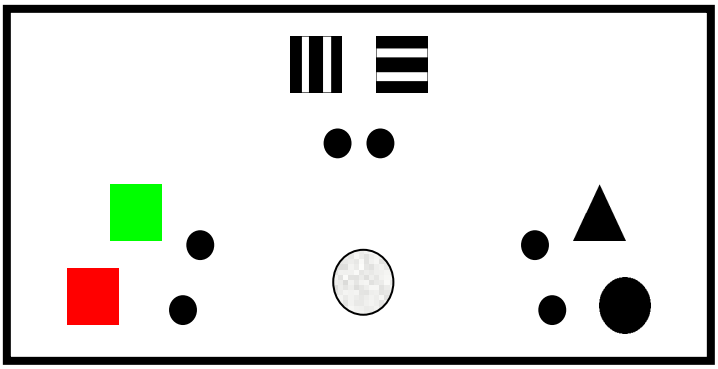


Figure 3. The response box used for all experiments. The small black circles represent the response buttons, while the white center circle represents the finger rest pad.

Words directly signifying the task, printed in all capital letters ("COLOR," "LINE" and "SHAPE") served as cues for each task. On approximately one third of the trials participants repeated the same task that they performed on the previous trial, while they were required to switch to a new task on approximately two thirds of the trials. Half of the task switch trials were Backward Inhibition conditions that required participants to switch back to the task that was performed on trial N-2 (e.g., **Color** → Line → **Color**), while the other half were not (e.g., Shape → Line → **Color**). A task set inertia (TSI) variable was also included in the task switch conditions, with the task from trial N-1 serving as the distractor in one half of the trials (e.g., **Cl → Sc**). In the other half of trials the recently abandoned task was not used as the distractor (e.g., Cl → Sl). The BI and TSI variables were crossed and counterbalanced across CTIs, resulting in the task switch conditions listed in Table 2.

Results

Error trials, trials immediately following an error, and trials with RTs less than 200 ms or greater than 2000 ms were excluded from the RT analyses. Because the BI

Table 2. Task switch conditions for Experiment 1A.

Trial N-2	Trial N-1	Trial N	Condition
COLOR/line	LINE/color	SHAPE/color	• No BI • No TSI
COLOR/line	LINE/color	COLOR/shape	• BI • No TSI
COLOR/line	LINE/color	SHAPE/line	• No BI • TSI
COLOR/line	LINE/color	COLOR/line	• BI • TSI

Note: The relevant stimulus attribute is written in CAPS listed first, while the irrelevant (distractor) attribute is written in lowercase, listed second. For example, a color task stimulus with irrelevant line orientation information would be labeled "COLOR/line".

factor required that each trial be coded relative to trial N-2, the first two trials of each block were also excluded. Trials immediately following an error, trials with RTs less than 200 ms or greater than 2000 ms, and the first two trials of each block were excluded from the accuracy analyses. Within-subject median RTs and accuracy rates were then computed for each condition.

Overall Analyses

A 2 (Task Switch) x 2 (CTI) x 3 (Task) analysis of variance (ANOVA) was used to measure an overall switch cost as well to assess the overall difficulty of the three tasks. As expected, the task switch cost was reliable, $F(1,35) = 87.41$, $p < .05$, with task repeat trials (M = 566 ms) being faster than task switch trials (M = 666 ms), resulting in a 100 ms switch cost. CTI was also significant, $F(1,35) = 173.40$, $p < .01$, with faster RTs at the long CTI (M = 581 ms) than at the short CTI (M = 652 ms). Task Switch and CTI

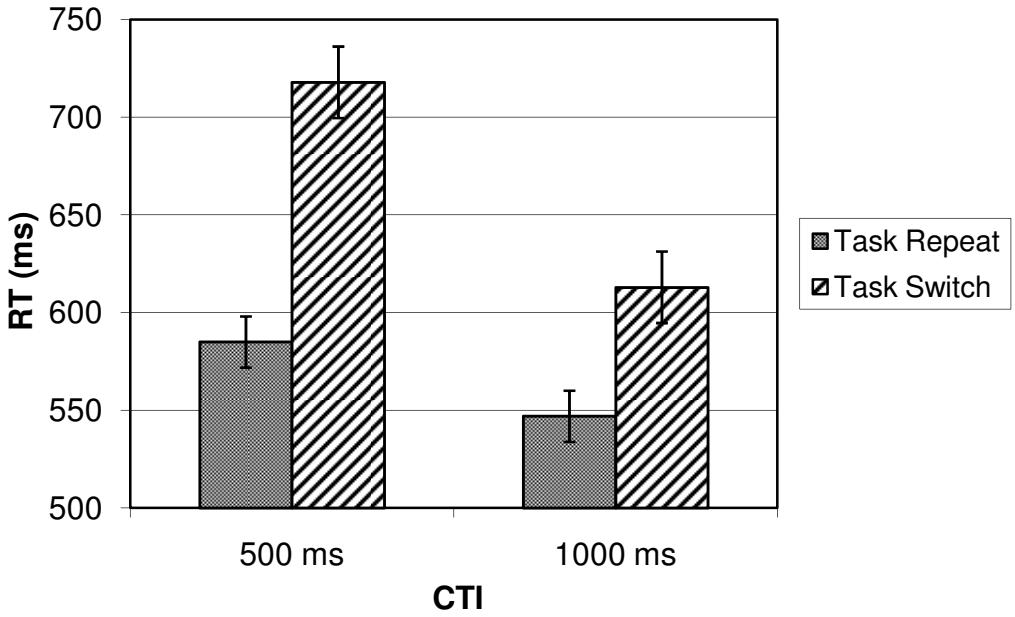


Figure 4. Task Switch x CTI interaction for Experiment 1A.

significantly interacted (see Figure 4), $F(1,35) = 45.00$, $p < .01$, with significantly longer switch costs at the short CTI (106 ms) than at the long CTI (37 ms). This result suggested that the participants used the CTI to prepare for the new task (see Rogers & Monsell, 1995). It should also be noted that the three tasks did differ significantly in their overall difficulty, $F(2,35) = 21.74$, $p < .01$, with color being the fastest of the three (M = 578 ms), followed by shape (M = 616 ms), while the line orientation was the slowest task overall (M = 655 ms). Task RTs did not interact with Task Switch or CTI, suggesting that the task switching or cue based preparatory processes did not differ significantly with the difficulty of the three tasks.

The same factors were included in an ANOVA conducted on the accuracy data. The main effects for Task Switch, $F(1,35) = 21.02$, $p < .01$, and CTI, $F(1,35) = 14.09$, $p < .01$, mirrored the RT effects with faster RTs generally corresponding to greater

accuracy. Participants were significantly more accurate when repeating a task on consecutive trials (M = .980) than when switching tasks (M = .960), and they were more accurate at longer CTIs (M = .975) than at shorter CTIs (M = .966). The interaction between Task Switch and CTI was also again significant, $F(1,35) = 5.92$, $p < .05$, with little difference between the short (M = .979) and long (M = .981) CTIs when the task was repeated, but a larger difference between the short (M = .952) and long (M = .968) when the task switched. The main effect for Task was also significant, $F(2,35) = 7.97$, $p < .01$, with the color task (M = .980) showing greater accuracy than the line orientation(M = .965) and shape (M = .967) tasks. Task did not interact with Task Switch or CTI in terms of accuracy.

Backward Inhibition and Task Set Inertia Analyses

The second analysis investigated potential BI and TSI effects (see Table 2 for conditions). A 2 (BI) x 2 (TSI) x 2 (CTI) ANOVA was conducted within the task switch trials only. The main effect for BI was significant, $F(1,35) = 4.65$, $p < .05$, such that trials in which backward inhibition was present (**C→L→C**; M = 677 ms) resulted in longer RTs than those in which it was not present (S→L→C; M = 658 ms). This result serves as a replication of Mayr and Keele's (2000) observed BI effect, but with bivalent as opposed to trivalent stimuli, suggesting there is a significant cost for reactivating a recently abandoned task. The main effect for TSI was also significant, $F(1,35) = 5.89$, $p < .05$, but in the opposite direction predicted by the TSI account. Trials in which the recently abandoned task (the task performed on trial N-1) was used as irrelevant, distracting information on trial N were significantly *faster* (M = 662 ms) than situations in which information from the trial N-1 task was absent in trial N (M = 673 ms). This result

suggests that recently performed tasks create *less* interference than information from a task not performed as recently, providing further evidence that abandoned tasks are actively inhibited instead of passively decaying. The effects for BI and TSI are listed in Table 3. The main effect for CTI was also significant, $F(1,35) = 139.96$, $p < .01$, with the long preparation intervals resulting in longer RTs (M = 619 ms) than the short intervals (M = 716 ms). CTI did not, however, interact with BI or TSI.

The same ANOVA was run for the accuracy data, revealing a significant effect for BI (see Table 3), $F(1,35) = 9.76$, $p < .01$, where BI conditions were significantly less accurate (M = .954) than conditions without BI (M = .966), as well as a main effect for CTI, $F(1,35) = 10.24$, $p < .01$, where short CTIs were less accurate (M = .952) than long CTIs (M = .967). No significant accuracy effect was found for TSI. As with the first analysis, accuracy rates were generally high, but where significant effects were found longer RTs generally corresponded with higher accuracy rates, showing no evidence of a speed-accuracy tradeoff.

Although the overall difficulty of the tasks differed significantly, we did not find a Task interaction with Task Switch or CTI (although see Allport et al. 1994; Allport & Wylie, 1999). It could be the case, however, that inhibition is applied differently to each of the three different tasks used in this experiment (see Mayr & Keele, 2000). Thus, based on the significant Task and BI main effects reported in the previous analyses we conducted a 3 (Task) x 2 (Backward Inhibition) posthoc ANOVA for the RT data. The analysis revealed main effects for Task, $F(1,35) = 12.11$, $p < .01$, and Backward Inhibition, $F(1,35) = 6.38$, $p < .05$. The interaction was also significant, $F(2,35) = 4.38$, p

Table 3. Exp. 1A: Mean RT and accuracy (and standard error) for Backward Inhibition (BI) and Task Set Inertia (TSI).

	RT	Accuracy
No BI	658 ms (17.1)	.966 (.004)
BI	677 ms (20.0)	.954 (.006)
BI Cost	**19 ms***	**-.012***

	RT	Accuracy
No TSI	673 ms (18.5)	.961 (.005)
TSI	662 ms (17.9)	.959 (.006)
TSI Cost	**-11 ms***	**-.002**

< .05, with no inhibition occurring for the color task but significant inhibition occurring for both the line orientation and shape tasks (see Figure 5).

Discussion

Experiment 1A replicated the expected effects in a task switch paradigm: There is a cost in RT and accuracy for switching tasks, relative to repeating a task, but that cost diminishes as the preparation time (CTI) between the task cue and the target increases. Of greater interest in this experiment, however, was the opportunity to investigate how inhibitory processes and/or proactive interference from the previous task may contribute to switch costs.

Norman and Shallice (1980/1986) argued that when one schema is activated, all other schemas are inhibited. The results from Experiment 1A suggest that this statement must be qualified at least to the extent that the most recently performed task schema is inhibited significantly more than others. These results support the notion that activation levels of switched-away-from tasks do not simply passively decay (i.e., Allport et al.

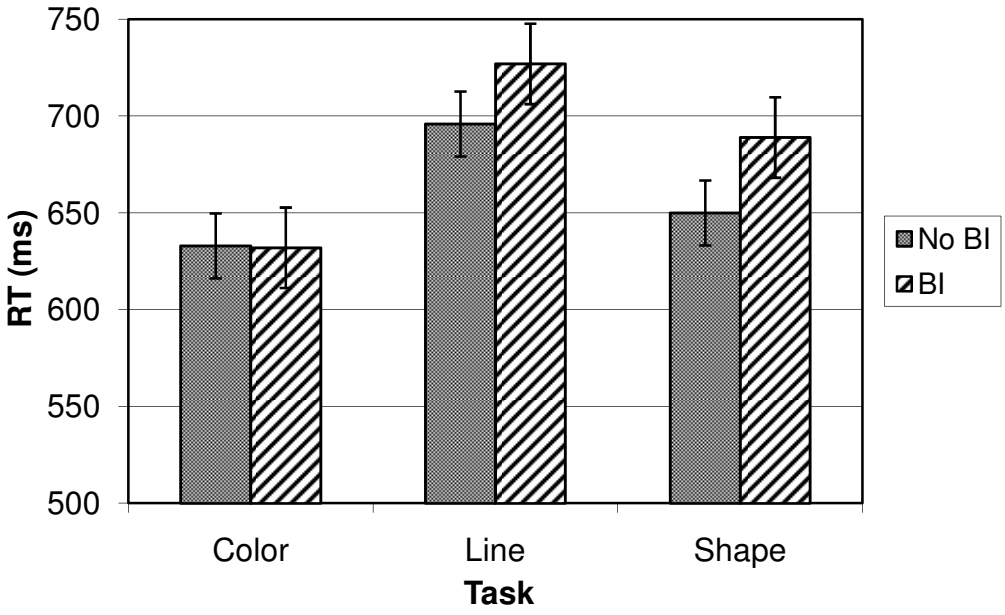


Figure 5. Task X Backward Inhibition in Experiment 1A.

1994; Allport & Wylie, 1999) from working memory, but rather that they are inhibited (i.e., Mayr & Keele, 2000). Specifically, Mayr and Keele suggested that in order to switch from task A to task B, task A must be inhibited; if task A is reinstated on the next trial, it will take longer to reactivate it than another task. Experiment 1A replicated this finding: participants were significantly slower and less accurate in switching back to a recently inhibited task (e.g., **A-**B-**A**) than they were in switching to a task that was not recently performed, and thus not recently inhibited (e.g., A-B-**C**).

This experiment also considered whether Task Set Inertia (i.e., Allport et al., 1994) plays a role in the switching process. In contrast to backward inhibition, TSI suggests that the previous tasks cause interference, thus contributing to switch costs. In this experiment, we might have expected to see evidence of TSI in carry-over effects in the irrelevant dimension of a target. That is, TSI interference would be demonstrated if switch costs are larger when the irrelevant dimension of a target was present on the

previous trial (e.g., Cs→Lc). Interestingly, however, the TSI effect of Experiment 1A was significant in the *opposite* direction. Irrelevant information from the most recently performed task created significantly *less* interference than irrelevant information from a task that was not performed as recently. This result, in combination with the backward inhibition effect, strongly supports the contention that the most recent task is inhibited during task switching and thus creates less interference relative to other sources of distracting information.

One could argue, as Mayr and Keele (2000; see also Mayr, 2007) have, that a function of task set inhibition is to reduce interference stemming from recently performed task sets when performing a new task. These results support that interpretation. The boundaries of this explanation will be tested more explicitly in Experiment 1B, where we examine backward inhibition in a design consisting of exclusively univalent stimuli, where no interference from irrelevant task information is present in the target stimuli.

It is also noteworthy that neither Backward Inhibition nor TSI interacted significantly with CTI. One reason may stem from the problem of measuring inhibition only indirectly in the present paradigm, as an increased cost (in the RT of trial N) associated with overcoming the inhibition that was applied after trial N-2. This inhibition is likely to decay (see Mayr & Keele, 2000) to differing degrees across the trials and processes that occur between the time the inhibition was applied and when an RT for trial N is measured. Moreover, it is important to note that Mayr and Keele (see Experiments 1A and 1B) observed that backward inhibition was relatively unaffected by, and appeared to be "immune" to, advance task set preparation. Experiment 2 was designed to shed light on this problem by measuring inhibition during the trial it occurs, as opposed the

measuring overcoming that inhibition on later trials. We will return to this issue in the general discussion, where the relationship between preparation time and inhibition of task sets can be discussed in light of the results of all three experiments.

Finally, Mayr and Keele (2000, Experiment 1A) observed a relatively small backward inhibition effect associated with their color task. Experiment 1A essentially replicated this effect, too, by finding no inhibition associated with the color task, but significant inhibition with the line orientation and shape tasks. The simplest explanation would be that easier tasks (such as color identification, which was the easiest of our three tasks in terms of RT and accuracy) may not be inhibited, as they may be easier to switch away from. However, our tasks are fairly similar in difficulty, with overall task differences accounting for less than 10% of the total RT. It seems unlikely that such a small difference in task difficulty could account for essentially a 100% reduction in inhibition. Further research is needed with different combinations of tasks to better understand why inhibition appears to be associated with some tasks but not others.

EXPERIMENT 1B

Mayr and Keele (2000) suggested that in situations where there is less competition among task sets one might expect to find less inhibition of irrelevant or recently abandoned tasks. They suggested that inhibition develops as a result of a build-up of conflict resolution processes in responding to multivalent stimuli, and little inhibition may occur if conflict resolution processes are not necessary. Other evidence has suggested that the amount of inhibition present may be modulated by overall experimental task demands. For example, Schuch and Koch (2003) found no BI associated with disengaging from tasks on trials that did not require a response. Additionally, our previous research has indicated that inhibition of specific value level dimensions may depend on the proportion of multivalent stimuli, or stimuli requiring the resolution of conflict, in the task design (Costa, 2005; Costa & Friedrich, 2006).

Although Mayr and Keele (2000) assumed that task set competition within a multivalent stimulus was important, their experiments did not directly investigate whether conflict resolution within a target is a *necessary* condition for inhibition to occur. In this experiment, we examined whether inhibition occurs only when there is potential conflict from the task that must be disengaged from (i.e., an upcoming multivalent stimulus) or whether it occurs in all task switching scenarios, regardless of whether conflict resolution is necessary. We utilized univalent stimuli, or stimuli that pertain to only one task and thus entail no conflict resolution, to see if the BI effect found by Mayr

and Keele and in our Experiment 1A would still be present. If inhibition of the previous task is a result of the process of conflict resolution, then we should find no BI throughout the experiment, as all trials are univalent. However, if inhibition of previous tasks occurs as a result of the task switch process per se, and occurs even in the absence of conflict within the target stimulus, then we should expect to find a significant BI effect.

Moreover, this univalent design allows us to utilize the task switching paradigm to investigate potential inhibition in manner that does not allow for the problematic competing explanations of the negative priming effect. The univalent stimuli do not have irrelevant dimensions that must be ignored, thus there can be not "do not respond" goal or "tag" placed on any particular stimulus or stimulus value. Every instance of a stimulus is associated only with a valid response. Thus, non-inhibitory, episodic retrieval models cannot account for any observed RT costs in conditions involving backward inhibition in this experimental design.

Method

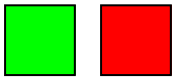
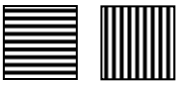
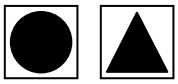
Apparatus and Participants

Apparatus and participant recruitment were the same as described in Experiment 1A. Thirty-six students participated in this experiment.

Tasks and Stimuli

The same three tasks as in Experiment 1A were used, but in this experiment the stimuli were univalent, or contained values pertaining to only the relevant task. The tasks and stimuli are listed in Table 4.

Table 4. Stimuli for Experiment 1B.

Stimulus	Task/Cue	Targets	Responses
C	COLOR		Green/Red
L	LINE		Horizontal/Vertical
S	SHAPE		Circle/Triangle

Procedure and Design

The training procedure, response board, and general experimental procedure were the same as in Experiment 1A. The same task cues and CTIs were also used, with half of the trials having the short (500 ms) interval and half having the long (1000 ms) interval. Once again, the task repeated on approximately one third of the trials and switched on the other two thirds. Half of the task switch trials required reactivating the task from trial N-2 (BI), while the other half did not (no BI). TSI was not examined in this experiment, as all targets were univalent and thus had no irrelevant, interfering dimension.

Results

Overall Analyses

The data trimming procedures were the same as described for Experiment 1A. A 2 (Task Switch) x 2 (CTI) x 3 (Task) ANOVA was conducted on the median RT data to measure an overall switch cost, preparation effects, and difficulty of the three tasks. The

main effects for Task Switch, $F(1,35) = 109.37$, $p < .01$, and CTI, $F(1,35) = 143.32$, $p < .01$, were again significant, with task repeat trials (M = 487 ms) being faster than task switches (M = 560 ms) and long CTIs (M = 494 ms) being faster than the short CTIs (M = 552 ms). The interaction between Task Switch and CTI was once again significant, $F(1,35) = 60.07$, $p < .01$, with a smaller switch cost at the long CTI (45 ms) than at the short CTI (99 ms). As in the first experiment, there was a main effect for Task, $F(2,35) = 30.53$, $p < .01$, with color being the overall fastest task (M = 488 ms), followed by shape (M = 529 ms), then line orientation (M = 554 ms). Task did not interact with Task Switch or CTI.

The same ANOVA was run on the accuracy data, although it should be noted that overall accuracy rates were very high (M = .987), and accuracy rates generally mirrored RT findings, with the exception of the two-way interactions described below. This ANOVA revealed a significant main effect for Task Switch, $F(1,35) = 12.50$, $p < .01$, with task repeats more accurate (M = .991) than task switches (M = .983). The main effect for Task was also significant, $F(2,35) = 18.21$, $p < .01$, with the color and shape tasks (M = .991 for both tasks) being more accurate than the line orientation task (M = .978). There was no main effect for CTI, but CTI did interact with Task Switch, $F(1,35) = 15.28$, $p < .01$, and Task, $F(2,35) = 4.27$, $p < .05$. For task repeat trials, participants were more accurate at the short CTI (M = .994) than at the long (M = .987), while for task switch trials, participants were more accurate at the long CTI (M = .986) than at the short (M = .979). At the short CTI the participants were most accurate performing the color task (M = .991) followed by the shape task (M = .988), but at the long CTI,

participants were most accurate on the shape task (M = .994), followed by the color task (M = .992). The line orientation task was the least accurate at both the short (M = .982) and long (M = .975) CTI.

Backward Inhibition Analyses

A 2 (BI) x 2 (CTI) ANOVA was also conducted within the task switch trials. This test revealed a significant main effect for BI, $F(1,35) = 21.28$, $p < .01$, with backward inhibition conditions resulting in significantly longer RTs than when the most recently abandoned task did not need to be reactivated (see Table 5). The main effect for CTI was also significant, $F(1,35) = 169.99$, $p < .01$, with short CTIs (M = 600 ms) resulting in longer RTs than long CTIs (M = 513 ms); however, CTI did not interact with BI.
The same ANOVA run on the accuracy data revealed significant main effect for BI, $F(1,35) = 4.26$, $p < .05$, and a marginally significant main effect for CTI, $F(1,35) = 4.02$, $p = .53$. The accuracy effects were in the same direction as the RT effects (with lower accuracy corresponding to longer RTs), with the No BI conditions more accurate than the BI conditions (see Table 5), and the long CTIs (M = .986) more accurate that the short CTI (M = .980).

Table 5. Exp.1B: Mean RT and accuracy (and standard error) for Backward Inhibition (BI).

	RT	Accuracy
No BI	548 ms (15.6)	.986 (.002)
BI	564 ms (15.3)	.981 (.003)
BI Cost	**16 ms***	**-.005***

The main effects for Task and Backward Inhibition were significant, so we once again conducted a 3 (Task) X 2 (Backward Inhibition) ANOVA on the RT data. The posthoc analysis revealed main effects for Task, $F(1,35) = 12.11$, $p < .01$, and Backward Inhibition, $F(1,35) = 6.38$, $p < .05$, and the interaction was also significant, $F(2,35) = 4.38$, $p < .05$. As in Experiment 1A, the analysis showed that no backward inhibition occurred for the color task but significant inhibition occurred in the shape and line orientation tasks (see Figure 6).

Discussion

As in Experiment 1A, we found significant RT and accuracy costs for switching tasks, with the RT switch cost reduced at the longer CTI. This suggests that participants are endogenously preparing new task sets (see Rogers & Monsell, 1995), but a residual switch cost remains even with long preparation intervals and univalent stimuli.

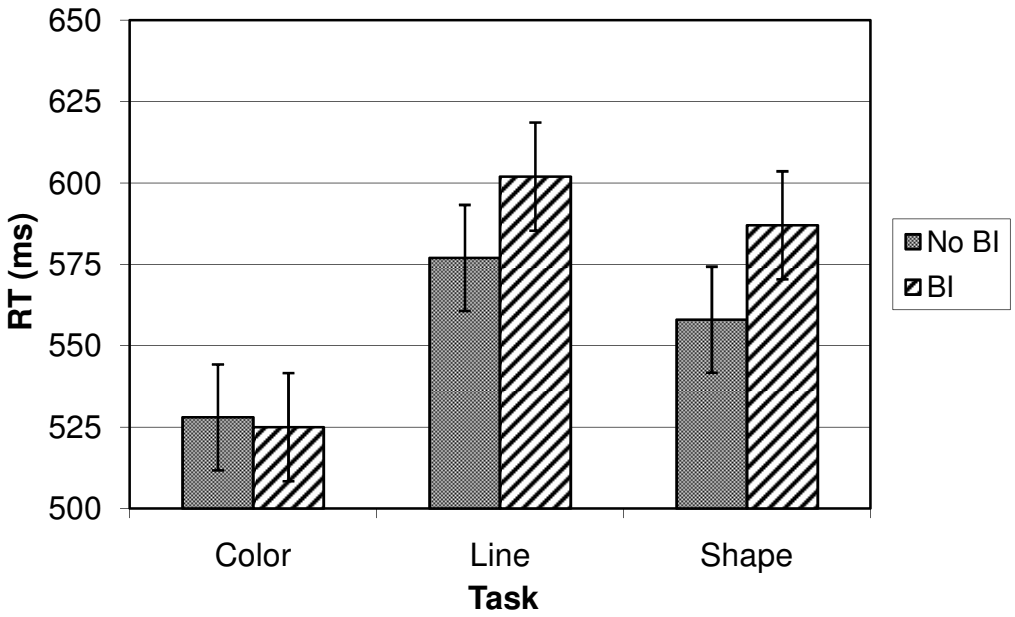


Figure 6. Task X Backward Inhibition for Experiment 1B.

Comparing these results with those of the previous experiment, we find that RTs were faster and more accurate for univalent (Exp. 1B) than bivalent (Exp. 1A) stimuli overall, but the task switching and preparation processes appear to be the same for the two types of stimuli. The Task X Backward Inhibition interaction was also replicated, with the color task again being associated with no inhibition.

Most importantly, we also observed significant backward inhibition in a series of trials that contained only univalent stimuli and univalent response mappings. It has been argued that backward inhibition develops out of the build-up of conflict resolution processes between task sets after the target onset (see Mayr & Keele, 2000, footnote 2). The presence of significant backward inhibition with univalent stimuli demonstrates that conflict between multiple dimensions of the target stimulus *is not necessary* for inhibition to develop or occur. Inhibition then, appears to occur not to reduce potential interference within an upcoming target, but as a more general process of disengaging from old tasks.

It is important to note that the significant inhibition effects found in this experiment cannot be accounted by episodic retrieval accounts, or accounts that suggest RT costs stem from having to overcome a "do not respond tag" that was applied to a stimulus or stimulus aspect on prior instances. Negative priming paradigms, out of which such non-inhibitory accounts were developed (see Neill & Valdes, 1992; Neill et al., 1992), use stimuli that have an aspect that must be responded to and an aspect that must be ignored. Similarly, traditional task switching paradigms that use multivalent stimuli have a goal-relevant stimulus dimension that must be responded to and interfering, irrelevant dimension(s), that must be ignored. The univalent stimuli utilized in this experiment, however, only have a goal relevant dimension; they did not have an

irrelevant dimension. Thus there was no stimulus-level information that must be ignored in the univalent stimuli, so explanations that utilize “do not respond” tags cannot sufficiently explain the observed RT costs found in the inhibition conditions of this experiment.

Finally, Experiment 1B also serves to justify the use of univalent stimuli in Experiment 2. The design and cues to be utilized in Experiment 2 require the use of univalent stimuli, so it was critical before implementing such a design to establish that both switch costs and backward inhibition do indeed occur in trial sequences that utilize only univalent targets.

EXPERIMENT 2

One of the major problems associated with measuring inhibitory processes for both negative priming and for backward inhibition in task switching paradigms has been that inhibition itself is not directly observed. Rather, inhibition is inferred based on increased RTs associated with overcoming inhibition from previous trials. In negative priming paradigms, inhibition is inferred through the slowing of a response to a target that had been ignored on a previous trial (e.g., Tipper, 2001). In task switching, backward inhibition is inferred through longer RTs for switching to a task that had been more recently abandoned. Although the mechanisms responsible for each form of inhibition may differ (see Mayr & Keele, 2000), both paradigms indirectly measure inhibition that occurred on a previous trial. More specifically, both paradigms measure additional processing time necessary to *overcome* inhibition that was assumed to occur on a previous trial. These indirect measures have provided data that suggest inhibitory processes are occurring but have also left room for alternative explanations for the apparent inhibitory processes.

Experiment 2 provides a way to potentially measure inhibition within the trial it is assumed to occur on, rather than measuring the process of overcoming of previous inhibition. In both the alternating runs (e.g., Rogers & Monsell, 1995) and explicit cueing paradigms (e.g., Meiran 1996, 2000) used to study task switching, the participants are aware of the task they will perform on the upcoming trial in advance of the onset of the

target stimulus. Thus, they can begin activating or reconfiguring the new task *and* potentially begin inhibiting or disengaging from the old task in advance of the target (Mayr & Keele, 2000). Activation and inhibition processes and the benefits in RT associated with each process are confounded in the pretrial period. The present experiment introduces a method by which these processes can be separated by using three tasks and a form of "transition" cues (Fortsmann, Brass, & Koch, 2005; Schneider & Logan, 2007) that inform the participant whether to switch tasks ("SWITCH") or repeat the same task ("REPEAT") in advance of the target. These transition cues, however, do not inform the participant which of the three tasks will be upcoming. In the task switch condition, this potentially will allow the participants to begin switching away from or inhibiting the old task without allowing them to begin reconfiguring the new task, because they do not know which of the two potential other tasks will follow. For example, if participants perform the Color task on trial N-1 and is then given a "SWITCH" cue, they can begin switching away from the Color task but cannot begin to prepare the Line or Shape task, because they do not know which of the two potential tasks will be upcoming. In this way, we will be able to directly measure the RT benefits associated with inhibiting the old task separately from the benefits of preparing the new task. Moreover, we will be able to measure the time course of the inhibition of task sets through the use of a CTI variable, an observation that was not possible in previous paradigms that measured backward inhibition.

Method

Apparatus and Participants

The apparatus and recruitment processes were the same as described in the previous two experiments.

Tasks and Stimuli

The three tasks from the earlier experiments were used again. The experiment utilized only univalent stimuli, as in Experiment 1B (see Table 2).

Procedure and Design

The training procedure, response setup, and general experimental procedure were the same as described in the earlier experiments. As in the previous experiments CTIs of 500 ms (short) and 1000 ms (long) were used and approximately one third of the trials were task repeats and two thirds were task switch trials. In this experiment, however, in addition to using the explicit task cues of "COLOR," "LINE," and "SHAPE," to cue the respective tasks, we also included neutral cues ("XXXXX") that contained no information relevant to the upcoming task, as well as transition cues that instructed the participant to switch tasks ("SWITCH") or repeat the same task ("REPEAT"). The logic of the "SWITCH" cue is that, like the "XXXXX" cue, it does not allow the participants to prepare the specific upcoming task. However, unlike the "XXXXX" cue, it does potentially allow them to begin disengaging from or inhibiting the previously performed task. This cue type allowed us to separate performance benefits associated with preparing the new task in advance (i.e., the explicit cues) from benefits associated only with disengaging from the previous task (i.e., the transition cues), which we can compare to

cues from which participants receive no useful information in advance (see Table 6). Each cue type appeared in approximately equal frequency (one third explicit, one third process, and one third neutral cues) and was counterbalanced across task repeat and task switch trials and the two CTIs.

Results

For the RT data, main effects for Task Switch, $F(1,35) = 225.52$, $p < .01$, and CTI, $F(1,35) = 103.46$, $p < .01$, were observed. Task repeat trials (M = 576 ms) were faster than task switch trials (M = 690 ms) and the long CTIs (M = 615 ms) were faster than the short (M = 651 ms). The interaction between Task Switch and CTI was also significant, $F(1,35) = 24.85$, $p < .01$, once again showing significantly larger costs for switching tasks at the short CTIs (126 ms) than at the long CTIs (102 ms).

Table 6. Cue Condition examples for Experiment 2. The top three rows depict task repeat conditions while the bottom three rows depict task switch conditions.

Trial N-1 Task	Trial N Cue	Trial N Task	Processes
Color	"COLOR" (Explicit)	Color	• Set maintenance • Explicit cueing of task
Color	"REPEAT" (Transition)	Color	• Set maintenance
Color	"XXXXX" (Neutral)	Color	• Possible set maintenance
Color	"SHAPE" (Explicit)	Shape	• Reconfiguration of new task (i.e., shape) • Explicit cueing of new task • Inhibition of N-1 task (i.e., color)
Color	"SWITCH" (Transition)	Shape	• Inhibition of N-1 task (i.e., color)
Color	"XXXXX" (Neutral)	Shape	• Possible set maintenance

The main effect for Cue Type was also significant, $F(2,35) = 117.26$, $p < .01$, with the explicit cues (COLOR/LINE/SHAPE) resulting in the fastest RTs (M = 578 ms), followed by the transition cues (REPEAT/SWITCH; M = 633 ms), and then the neutral cues (XXXXX; M = 689 ms). Cue Type also interacted with CTI, $F(2,35) = 25.86$, $p < .01$ (see Figure 7), reflecting the relative usefulness of the cue in preparing for a task switch. Post hoc dependent samples *t*-tests revealed a large benefit for the longer preparation times for the explicit cues [$t(35) = 8.61$, $p < .01$], a smaller but significant benefit for the transition cues [$t(35) = 6.82$, $p < .01$], and no significant RT benefit for the neutral cues [$t(35) = 1.50$, $p = .143$].

Of particular interest is the significant Cue Type X Task Switch interaction, $F(2,35) = 99.05$, $p < .01$. Post-hoc dependent sample *t*-tests conducted to examine this

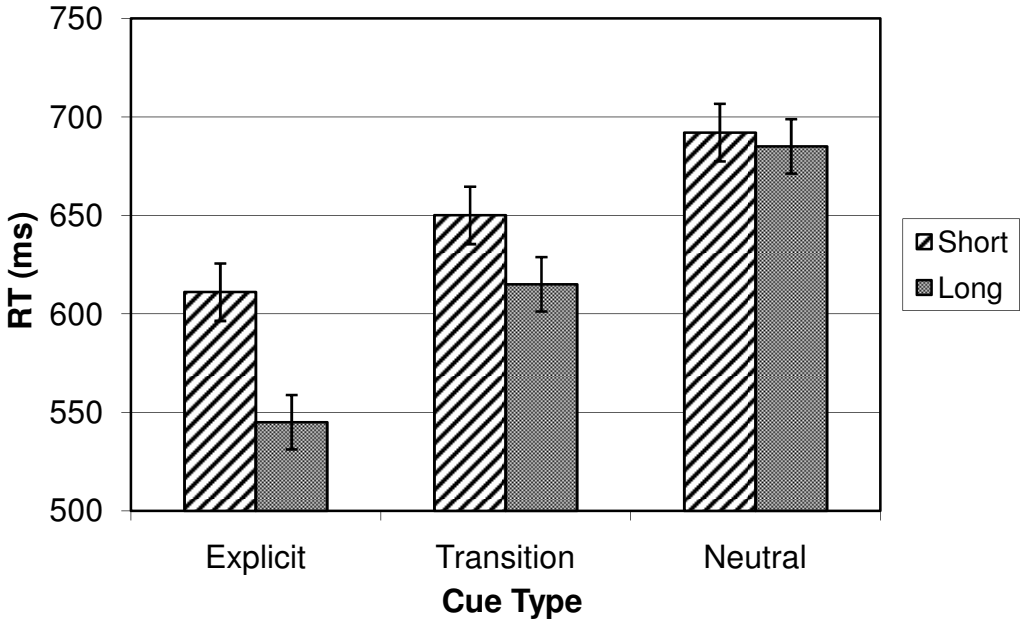


Figure 7. Cue Type X CTI for Experiment 2.

interaction showed that transition cues resulted in faster RTs than the explicit cues in the task repeat trials, $t(35) = 2.15$, $p < .05$, but that explicit cues were faster than the process cues in the task switch trials, $t(35) = 11.82$, $p < .01$. The neutral cues resulted in the longest RTs for both the task repeat and task switch conditions (see Figure 8). A final planned comparison dependent samples *t*-test showed that the transition cues were significantly faster than the neutral cues in the task switch condition, $t(35) = 4.86$, $p < .01$, demonstrating a significant benefit for the "SWITCH" cue compared to the neutral "XXXXX" cue.

The accuracy ANOVA for the same factors revealed a significant main effect for Task Switch, $F(1,35) = 7.56$, $p < .01$, with task repeat conditions (M = .985) being more accurate than task switch conditions (M = .974). The Task Switch X CTI interaction was appraoching significance, $F(2,35) = 4.09$, $p = .051$, with short CTIs being marginally

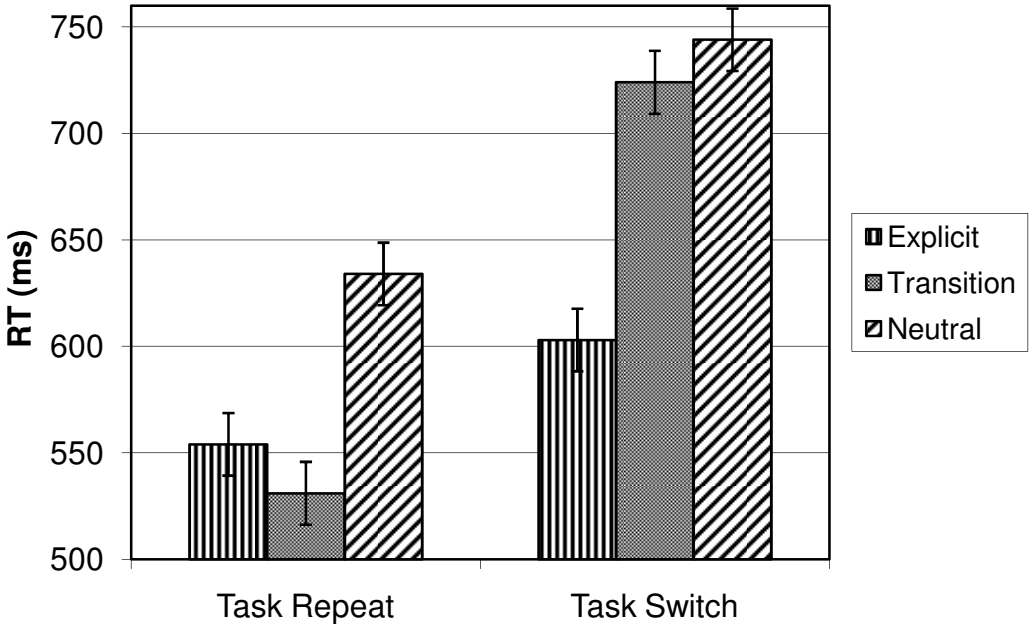


Figure 8. Task Switch X Cue Type for Experiment 2.

more accurate than long CTIs in the task repeat conditions (M = .987 and .983, respectively), but less accurate in the task switch conditions (M = .973 and .976, respectively). Finally, the Task Switch X Cue Type interaction was significant, $F(2,35) = 10.20$, $p < .01$, with the transition cues being less accurate (M = .974) than the explicit (M = .989) and neutral cues (M = .991) in the task repeat conditions, but more accurate (M = .977) than the explicit (M = .975) and neutral (M = .972) cues in the task switch conditions. This interaction reveals a speed accuracy trade-off for the transition cues in the task repeat conditions, where RTs were faster but responses less accurate.

Discussion

The results for Experiment 2 again replicate basic task switching effects, showing a significant switch cost and significant reduction of that switch cost with increased preparation time, and thus validating the use of the process cueing procedure used in this experiment. While longer preparation times (CTIs) were associated shorter RTs for both explicit and transition cues, no such benefit for preparation time was associated with the neutral ("XXXXX") cues, presumably because the latter cue type contained no useful information to prepare with during the CTI. It appears the amount of benefit is directly related to the amount of useful information in the cue. The explicit cues (and the "REPEAT" transition cue in the task repeat conditions) provided the participants with advance knowledge of the specific task that would be upcoming, and as expected those cues were associated with the largest benefits. The "SWITCH" transition cue informed the participants, in essence, that they would not be performing the task that they had performed on the previous trial, although it did not provide them with information as to what task to prepare for on the upcoming trial. Even so these cues were associated with

significant benefits relative to the neutral cues in the task switch conditions, demonstrating some performance benefit for being able to inhibit the previously performed task, even if the upcoming task cannot be prepared. We were thus able to observe significant benefit for task set inhibition that was not confounded by task set preparation. Moreover, we were able to measure this RT benefit of inhibition within the trial it occurred, as opposed to measuring inhibition indirectly, as a reactivation cost.

GENERAL DISCUSSION

The experiments reported here used three variations of the task switching paradigm to explore the issue of cognitive control, specifically to investigate the role of inhibitory processes in switching between multiple tasks. Experiments 1A and 1B replicated Mayr and Keele's (2000) backward inhibition effect, offering support for the notion that recent tasks are inhibited in the process of switching to performing a new task. These experiments provide evidence for inhibition with both univalent and bivalent stimuli and provide for a direct comparison between inhibitory and passive decay accounts of abandoned task sets. Experiment 2 examined the role of inhibition through the use of transition cues. The use of such cues allowed us to measure inhibition directly and separate the processes of inhibiting an old task from activating a new one. This experiment demonstrated that, when switching tasks, a specific inhibitory process does operate to disengage from the task performed on the previous trial.

Basic Task Switching Effects

Several results found across a wide variety of task switching paradigms (e.g., Liefooghe, Demanet, Vandierendonck, 2009; Meiran, 1996, 2000; Rogers & Monsell, 1995) generally are taken as evidence of an endogenous process of task set reconfiguration that is performed in advance of the onset of the target stimulus (but see Logan & Bundesen, 2003). First, trials in which the task performed in trial N-1 is

switched generally yield longer RTs and lower accuracy rates than trials in which the N-1 task is repeated, resulting in a switch cost. Longer preparation intervals (CTIs) yield shorter RTs overall and are also accompanied by a reduction in the switch cost. It is assumed that participants use the preparation intervals to prepare the new task in advance of the target stimulus. These effects, found in all three of our experiments, provide evidence of a control process of activating the new task set.

It is important that this pattern of effects also was found in Experiment 1B, which utilized only univalent stimuli. It has been argued (e.g., Meiran, 2000) that switch costs should occur only when there is competition or conflict within the target stimulus (i.e., multivalent targets) or at the response level (i.e., when one response key maps to both the triangle and red response). Neither source of conflict is present in the targets or response setup in Experiment 1B, yet the pattern of switch costs, and reduction of those costs with longer preparation intervals, appears the same as in Experiment 1A when multivalent stimuli were used. This manipulation is important because it removes the additional attentional demand of having to select between the relevant and irrelevant stimulus dimension in the target. Moreover, with multivalent targets potential effects stemming from the presence of irrelevant information in the target, such as negative priming of previously ignored information, may influence the task switching process (Costa, 2005). These factors may constitute significant components of the switch cost and the resolution of these sources of conflict may require cognitive control processes, but they are not specific to the process of switching between abstract task sets. Experiment 1B avoids these additional effects associated with response conflict and with the irrelevant target

dimension through the use of univalent stimuli and responses, and thus provides a more "pure" measure of the switch cost and of the benefits of advance preparation of task sets.

Experiment 2 provides a somewhat different but interesting window into the preparation processes following a cue. The interaction of Cue Type X CTI was significant, with a benefit for longer preparation times for the explicit and transition cues, but not for the neutral cues. The lack of benefit for the neutral cues at longer CTIs would be expected based on the logic of the endogenous task set reconfiguration model, as the neutral cues ("XXXXX") did not contain useful information with which to prepare – any of the three tasks could follow such a cue. Interestingly, the "SWITCH" transition cues were associated with a significant CTI benefit (see Figure 7) and were faster relative to the neutral cues in the task switch trials (see Figure 8). An activation-only model (e.g., Monsell & Mizon, 2006; Rogers & Monsell, 1995) would not be able account for such benefits because the "SWITCH" cues do not provide information allowing participants to prepare a specific task in advance of the target stimulus.

Task Set Inhibition

The most compelling empirical evidence that old task sets are inhibited when switching to a new task stems from backward inhibition (see Arbuthnott & Frank, 2000; Hubner, Deisbach, Haider, & Kluwe, 2003; Mayr & Keele, 2000; Shuch & Koch, 2003), in which switching back to recently abandoned task set results in a performance cost relative to switching to a task that was not recently abandoned. Such designs typically utilize three tasks where A-B-A task sequences are compared to C-B-A task sequences. The former sequence results in longer RTs, presumably because inhibition applied to task

A when switching away from it on trial N-1 must be overcome in order to reactivate task A on trial N.

In Experiments 1A and 1B we found significant backward inhibition associated with bivalent and univalent stimuli, respectively. The demonstration of backward inhibition is important in itself, but it is particularly notable that we observed a significant backward inhibition effect of roughly the same size for both the univalent and bivalent targets. Previously, Lien, Ruthruff, and Kuhns (2006) found that switch costs were insensitive to whether the previous trial was univalent or bivalent, and they suggest that inhibition is either weak or absent, easily overcome, or nonadaptive. The logic of their conclusions is based on the assumption that the incentive for inhibition would be stronger in the case of bivalent stimuli in which irrelevant task information within the target must be ignored. Our results, however, indicate that this is not the case. Rather, the presence and the strength of inhibition is insensitive to the valency of the target stimuli in the design. No target level or response level conflict or a need for conflict resolution within the target is required to trigger inhibitory processes. We find this result particularly important in terms of external validity because in many real world task switching scenarios, stimuli and responses are often not "multivalent," as they are in laboratory task switching scenarios. In real environments, we often switch attention between tasks and respond to stimuli that do not conflict in terms perceptual qualities or responses and these results suggest we still inhibit recently performed tasks in the process of switching to performing a new task in these situations. Inhibition of old tasks and old task information is not limited to multivalent stimuli.

Interestingly, we found significant inhibition associated with the shape and line orientation tasks, but not with the color task in both Experiments 1A and 1B (see Figures 5 & 6, respectively). A relatively small amount of inhibition associated with the color task was also found by Mayr & Keele (2000, Experiment 1a). One explanation for the lack of inhibition associated with the color task could stem from task difficulty; in our experiments, the color task was the fastest in terms of RT. However, the explanation that easy tasks are not inhibited seems oversimplified, for why would an approximate 10% reduction in latent RTs lead to essentially a 100% reduction in the amount of inhibition applied when disengaging from such a task? Other plausible explanations could stem from the nature of the color task or color processing and identification itself, and how this task differs from the other tasks used in our and Mayr and Keele's designs. Because backward inhibition is a measure of *overcoming* inhibition applied previously to a task set, it could be the case that color task dependent inhibition is easier to overcome, resulting in smaller or insignificant costs for reactivating that particular task. Understanding when inhibition is applied and when it is not could have important implications more generally for cognitive control, but further research is needed to resolve this question.

We did not observe significant interactions between Backward Inhibition and CTI in Experiments 1A and 1B. This finding also replicates a similar observation by Mayr and Keele (2000, Experiments 1a & 1b), in which they conclude backward inhibition seems “immune” to advanced preparation. The CTI of trial N, however, is not the interval in which the observed inhibition is assumed to occur; rather, the CTI is the interval in which preparation (or reactivation) of the new task is performed. It may be the case that

roughly the same amount of preparatory benefit can be received from increased CTIs when reactivating a task that was recently inhibited or when preparing one that was not recently inhibited.

Experiment 2 incorporated transition cues, which were designed to trigger the process to be performed (repeat the previous task or switch to a new task) without explicitly triggering the specific task to be performed on the upcoming trial. In the case of the 'SWITCH" cue, the participants could not begin preparing the new task because they did not know which of the two other tasks would be upcoming; however, they could possibly begin disengaging from the old task because they knew the task would be switched. This design allowed us to decouple processes related to preparing the new task from processes related to disengaging from old tasks. We found a significant benefit for this "SWITCH" relative to the neutral "XXXXX" cue, which suggests that significant RT benefits are associated with being able to perform only disengagement processes in advance of the cue. It has not been possible to investigate this possibility with previous research utilizing transition cues because in those cases only two tasks were used and thus, in the case of the switch cues, participants always knew which task they would be performing in advance of the target. It should be noted that in this experiment we did find a significant benefit for these transition cues at the longer preparation intervals (see Figure 7), where we were able to measure inhibition more directly, during the trial it was applied. These findings support the notion that inhibition is an active, endogenous control process.

Task Set Inhibition Versus Task Set Inertia

Allport et al. (1994; see also Allport and Wylie, 1999) have suggested that previously relevant task information retains persisting facilitation, know as task set inertia, that creates proactive interference in later trials, especially when the target stimuli on those trials are bivalent and contain information from the previously relevant task. Meiran (2000) provided supporting evidence of TSI by demonstrating that interference from the previous task is diminished when the interval between the response from one trial and the cue for the next is increased. This explanation of what happens during a task switch contrasts that of Mayr and Keele (2000), who argued that the activation level of the previous task set is actively inhibited and thus does not persist to the next trial. As noted previously, however, the studies that demonstrated TSI used only two tasks so that analyses of the relative activation level of the disengaged task were not possible. Similarly, Mayr and Keele's design, using trivalent stimuli so that aspects of all possible task sets were present in the target stimulus, did not allow an analysis of whether the abandoned task interfered if it appeared as an irrelevant dimension in the target.

In Experiment 1A, each target had one relevant and one irrelevant dimension, so it was possible to compare performance when the irrelevant dimension was the abandoned task from the previous trial and when it was not. The model of Allport et al. would predict *more* interference when the target contained an irrelevant dimension from the task performed on trial N-1, because such a task set has the most inertia. Mayr and Keele's model would predict *less* interference from such a bivalent stimulus, as the task performed on trial N-1 has presumably been recently inhibited and thus should contain less activation as compared to other tasks. Our findings were clear: there was

significantly *less* interference when the irrelevant dimension was from the recently abandoned task. This result is consistent with and supports the evidence of backward inhibition, demonstrating that the disengaged task is inhibited rather than maintaining some persisting activation. While our results from Experiment 1A do not rule out the possibility that some residual activation of old task information could persist, we show that this interference is controlled through the inhibition of old task sets, such that information from the most recently performed task interferes less than information from other tasks. This finding also suggests that the process of inhibiting task sets has adaptive benefits, a notion challenged by previous work (see Lien, Ruthruff, & Kuhns, 2006).

In general, then, the results of these experiments suggest that the process of allocating attentional resources to a new task goal is not merely accompanied by passive deactivation of all other task goals. While such indirect deactivation may occur due to limited processing resources being allocated elsewhere, the present results show that recently abandoned tasks are deactivated *more* than all other irrelevant tasks. The fact that all irrelevant tasks are not deactivated equally suggests inhibition is applied to tasks that are switched away from and that this inhibition persists into later trials.

Conclusions

Overall, these experiments offer strong support to the notion that old task sets, or those from which attention is disengaged in order to perform a new task, are actively inhibited. These data cannot be accounted for with activation-only models. Employing the task switching paradigm as opposed to negative priming or other paradigms to study these inhibitory control processes has allowed us to avoid several problems traditionally associated with studying inhibition.

In contrast to paradigms in which inhibition is assumed to occur at the stimulus or stimulus value level, the task set inhibition demonstrated in these experiments occurs on the abstract task set level (see Mayr, 2007; Mayr & Keele, 2000). This type of inhibition at the task set level is consistent with the original conception of executive control processes detailed in Norman and Shallice's (1980/1986) model. Moreover, the stimuli used in Experiment 1B and Experiment 2 were univalent and thus did not have irrelevant (and possibly competing or conflicting) dimensions or values that were ignored on a past trial but must be responded to on a subsequent trial. These univalent stimuli, then, cannot be said to be recalled with a "do not respond" memory trace that causes the observed pattern of results. Based on the present results, inhibition of the abstract task set serves as the best explanation to account for these data.

Although adding active inhibition to the set of control processes involved in task switching does add complexity, these experiments show that there may be performance benefits associated with such a process. Inhibition typically has been demonstrated as a cost for reactivating previously inhibited information, but in contrast we have shown that it also results in decreased interference from information associated with previously performed tasks (Experiment 1A). In everyday life, previously performed tasks or previously attended to information can interfere with current processing through remaining in working memory and drawing resources away from the current goal, even when there is no direct perceptual or response conflict between the old information and the new goal. We have demonstrated that inhibition does still occur in such situations (Experiment 1B). An inhibitory process that purges previously attended to information

from working memory could, in many scenarios, result in more efficient performance of the new task, and these experiments suggest that such a process does operate.

REFERENCES

Allport, A., Styles, E.A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 421-452). Cambridge, MA: MIT Press.

Allport, A., & Wylie, G. (1999). Task-switching: Positive and negative priming of task-set. In G.W. Humphreys, J. Duncan, &A. Treisman (Eds.), *Attention, space, and action: Studies in cognitive neuroscience* (pp. 273-296). Oxford, England: Oxford University Press.

Anderson, M. C., & Spellman, B. A. (1995). On the status of inhibitory mechanisms in cognition: Memory retrieval as a model case. *Psychological Review*, *102,* 68-100.

Arbuthnott, K. D., & Frank, J. (2000). Executive control in set switching: Residual switch costs and task-set inhibition. *Canadian Journal of Experimental Psychology, 54,* 33–41.

Arrington, C. M., Logan, G. D., & Schneider, D. W. (2007). Separating cue encoding from target processing in the explicit task-cuing procedure: Are there "true" task switch effects?*Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*, 484-502.

Braver, T. S., Cohen, J. D., Barch, D. M. (2002). The role of prefrontal cortex in normal and disordered cognitive control: A cognitive neuroscience perspective. In D. T. Stuss & R. T. Knight (Eds.). *Principles of frontal lobe function* (pp. 428-477). Oxford: Oxford University Press.

Breese, B. B. (1899). On inhibition. *Psychological Monographs, 3*, 1-65.

Broadbent, D. (1958). *Perception and communication*. London: Pergamon Press.

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review, 97,* 332-361.

Cohen, R. A. (1993). Neural mechanisms of attention. In R. A. Cohen (Ed.), *The neuropsychology of attention* (pp. 145-176). New York: Plenum Press.

Costa, R.E. (2005). Investigating the interference effects of the irrelevant task dimension in the task switching process. Unpublished master's thesis. University of Utah, Salt Lake City, UT.

Costa, R.E., & Friedrich, F.J. (2006, November). *Investigating task switching using univalent, neutral, and bivalent stimuli.* Presented at the annual meeting of the Psychonomic society, Houston, TX.

Dagenbach, D., & Carr, T. H. (Eds.). (1994)**.** *Inhibitory processes in attention, memory, and language.* San Diego: Academic Press.

Deutsch, J. & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological Review, 70*, 80-90.

Diamond, A. (1990). Developmental time course in human infants and infant monkeys, and the neural bases of inhibitory control in reaching. In A. Diamond (Ed.), *The development and neural bases of higher cognitive functions* (pp. 637–676). New York: New York Academy of Sciences Press.

Diamond, A., Kirkham, N. Z., & Amso, D. (2002). Conditions under which young children can hold two rules in mind and inhibit a prepotent response. *Developmental Psychology*, 38, 352–362.

Diamond, S., Balvin, R. S., & Diamond, F. R. (1963). *Inhibition and choice: A neurobehavioral approach to problems of plasticity in behavior.* New York: Harper *&* Row.

Forstmann, B.U., Brass, M., & Koch, I. (2007). Methodological and empirical issues when dissociating cue-related from task-related processes in the explicit task-cuing procedure. *Psychological Research*, 72(4): 393-400.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and new view. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 193-225). New York: Academic Press.

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (Eds.), *Attention and performance: XVII. Cognitive regulation of performance: Interaction of theory and application* (pp. 653-675). Cambridge, MA: MIT Press.

Houghton, G., & Tipper, S. P. (1994). A model of inhibitory mechanisms in selective attention. In D. Dagenbach & T. H. Carr (Eds.), *Inhibitory mechanisms in attention, memory and language* (pp. 53-112). San Diego: Academic Press.

Hübner, M., Dreisbach, G., Haider, H., Kluwe, R. H. (2003)**.** Backward inhibition as a means of sequential task-set control: evidence for reduction of task competition. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 29*(2):289-97.

James, W. (1890). *Principles of Psychology*. New York: Holt.

Johnston, W. A. & Heinz, S. P. (1978). Flexibility and Capacity Demands of Attention. *Journal of Experimental Psychology: General, 107*, 420-435.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Liefooghe, B., Demanet, J., & Vandierendonck, A. (2009). Is advance reconfiguration in voluntary task switching affected by the design employed? *Quarterly Journal of Experimental Psychology, 65,* 850-857.

Lien, M., Ruthruff, E., & Kuhns, D. (2006). On the difficulty of task switching: Assessing the role of task-set inhibition. *Psychonomic Bulletin & Review, 13,* 53-535.

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, *95*, 492-527.

Logan, G. D. (1990). Repetition priming and automaticity: Common underlying mechanisms? *Cognitive Psychology*, *22*, 1-35.

Logan, G. D. (2002). An instance theory of attention and memory. *Psychological Review*, *109*, 376-400.

Logan G. D. & Bundesen C. (2003). Clever homunculus: Is there an endogenous act of control in the explicit task-cuing procedure? *Journal of Experimental Psychology: Human Perception and Performance, 29*, 575-599.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin, 109(2),*163-203.

Mayr, U. (2007). Inhibition of task sets. In D. S. Gorfein & C. M. MacLeod (Eds.). *Inhibition in cognition* (pp. 27-44). APA Books: Washington DC.

Mayr, U., & Keele, S. (2000). Changing internal constraints on action: The role of backward inhibition. *Journal of Experimental Psychology: General, 129*, 4-26.

Mayr U., & Kliegl R. (2003). Differential effects of cue changes and task changes on task-set selection costs. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 362-372.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*, 1423-1442.

Meiran, N. (2000). Reconfiguration of stimulus task sets and response task sets during task switching. In S. Monsell and J. Driver (Eds.). *Attention and performance XVIII: Control of cognitive processes* (pp. 377-400). Cambridge, MA: MIT Press.

Meiran, N., Chorev, Z., & Shapir, A. (2000). Component processes in task switching. *Cognitive Psychology, 41*, 211-253.

Monsell, S., & Mizon, G. A. (2006). Can the task-cueing paradigm measure an "endogenous" task-set reconfiguration process? *Journal of Experimental Psychology: Human Perception and Performance, 32,* 493-516.

Neill, W. T. (1977). Inhibitory and facilitatory processes in selective attention. *Journal of Experimental Psychology: Human Perception and Performance, 3*, 444-450.

Neill, W. T., Mathis, K. M. (1998). Transfer-inappropriate processing: Negative priming and related phenomena. In Medin, D. L. (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 38, pp. 1-44). San Diego: Academic Press.

Neill, W. T., Valdes L. A. (1992). Persistence of negative priming: Steady state or decay? *Journal of Experimental Psychology: Learning, Memory, & Cognition, 18*, 565-576.

Neill, W. T., Valdes L. A., Terry, K. M., Gorfein, D. S. (1992). Persistence of negative priming: II. Evidence for episodic trace retrieval. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 18*, *993-1000.*

Norman, D.A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R.J. Davidson, G.E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation* (Vol. 4, pp.1-18). New York: Plenum.

Pillsbury, W. B. (1908). *Attention.* New York: Macmillan.

Posner, M. I. (1978). *Chronometric explanations of the mind.* Hillsdale, NJ: Erlbaum.

Potts, G. R., St. John, M. F., & Kirson, D. (1989). Incorporating new information into existing world knowledge. *Cognitive Psychology*, *21,* 303-333.

Rogers, R.D., & Monsell, S. (1995) Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*, 207-231.

Rubenstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 763-797.

Schneider, D. W., & Logan, G. D. (2007). Task switching versus cue switching: Using transition cuing to disentangle sequential effects in task-switching performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*, 370-378.

Schuch, S., & Koch, I. (2003). The role of response selection for inhibition of task sets in task shifting. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 92–105.

Smith, R. (1992). *Inhibition: History and meaning in the sciences of mind and brain.* Berkeley: University of California Press.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643-662.

Tipper, S. P. (1985). The negative priming effect: Inhibitory priming by ignored objects. *Quarterly Journal of Experimental Psychology, 37A*, 571-590.

Tipper, S. P. (2001). Does negative priming reflect inhibitory mechanisms? A review and integration of conflicting views. *Quarterly Journal of Experimental Psychology*, *54A*, 321-343.

Treisman, A. (1960). Contextual cues in selective listening. *Quarterly Journal of Experimental Psychology, 12*, 242-248.

Treisman, A. (1964). Monitoring and storage of irrelevant messages in selective attention. *Journal of Verbal Learning and Verbal Behavior, 3*, 449-459.

Wundt, W. (1902). *Grundzuge der physiologischen psychologie* [Principles of physiological psychology] (5th ed.). Leipzig, Germany: Engelman.